FUELS FOR JET PROPULSION

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FUELS FOR JET PROPULSION

AN ESSAY

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By

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BIOGRAPHICAL SKETCH OF THE AUTHOR

The author, Edward Chester Staehling, was born on August 19, 1920 in Chicago, Illinois. He attended Delta High School, Delta, Ohio, graduating in the class of 1938. From 1938 until 1942 he was a student at The Ohio State University, Columbus, Ohio. In June 1942 he was awarded the degree of Bachelor of Chemical Engineering from that Institution. Immediately following graduation from The Ohio State University, he was ordered to active duty in the United States Naval Reserve and has continued in that status during the past four years.

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FUELS FOR JET PROPULSION

Before undertaking detailed discussion of the fuels for jet propulsion, a description of the various types of jet-propulsion mechanisms and their uses is necessary to make clear the specific fuel requirements of each type. Arbitrarily, we can classify jet-propelled devices as:

- (1.) Rockets
  - (a.) solid propellents
  - (b.) liquid propellents
- (2.) Air-Stream Jets
  - (a.) athodyds
  - (b.) impulse ducts
  - (c.) turbojets

ROCKET MECHANISMS AND THEIR USES

The distinguishing feature of rockets is that they carry both the fuel and the oxidizing agent with which the fuel is burned.

Thermal jet rockets using solid fuels are used to assist in the take-off of flying boats and land planes and also are used to launch the "buzz-bomb" type of missile. The units develop a

high thrust for a short time, but after the reaction is started it cannot be controlled. Application to sustained flight is therefore not practical. Solid-propellent rockets are also useful for throwing charges over short distances as in the "bazooka".

Control of the jet is possible when liquid fuels are employed, as in the case of the German ME-163 fighter. Fuel and oxygen last only a few minutes if used continuously, but actually the ME-163 can stay in the air for a considerable time by soaring and gliding, using the thermal jet only in short spurts. Weight of the equipment is light in proportion to the power which can be developed; the only equipment is storage tanks for the fuel, means to deliver fuel to the burners, and the combustion chamber and nozzle.[2]

Rocket projectiles, as distinguished from aircraft, can make much more effective use of the thermal jet. Aircraft which depend on wings for support are limited in speed, while a projectile can move much faster than the speed of sound and can attain high propulsive efficiency as the rocket approaches the jet speed. Rockets would seem to have their chief application for flight above the atmosphere, as in the case of the V-2 bomb, or for possible interplanetary travel. With present fuels, the weight of propellant necessary to take a rocket projectile beyond the influence of the earth's gravity would have to be nearly ninety eight per cent of the initial total weight. When fuels are developed which utilize atomic energy, it will be possible to improve this figure greatly.[2]

AIR STREAM JET MECHANISMS AND THEIR USES

The general characteristic of air stream jets is that the propulsive gas is taken in from the surrounding atmosphere, heated by a burning hydrocarbon, and then exhausted at a higher velocity than that at which it entered.

One of these, the athodyd, is a suitably shaped duct equipped with fuel burners which, instead of using a compressor, relies on ram compression. "The heated gas is exhausted at a higher velocity than that at which it enters, thereby producing a net reactive force. An airplane so equipped must necessarily be launched by auxiliary means to provide ram pressure."[9]

The impulse duct or intermittent jet engine, like the athodyd, requires no compressor. "Employed in the German V-1 flying bomb and also produced in this country, the unit is simply a tube about ten feet long with a series of check valves at the front end and open at the rear. It operates on an intermittent cycle with a limited amount of compression resulting from the periodic surge of flame back and forth in the tube, which resonates like an organ pipe. Fuel is injected into the air as it streams past the check valves while the flame is surging to the rear; when the flame surges forward again, the pressure rise closes the check valves and the mixture explodes".[2]

Each air-stream jet engine of the above types has a characteristic combination of fuel economy, high-speed performance, and type of construction that adapts it to certain applications. Thermal

efficiencies are probably not over two per cent, but the units weigh only about one-third of a pound per horsepower and are inexpensive in construction. They are strictly expendable and consequently appear to have application only as missiles. "The air stream type of jet suffers a decrease in thrust as the operating altitude increases because the mass of the air handled decreases with decreasing air density. Thus a unit that delivers a maximum of one thousand pounds thrust at sea level at a given speed may be expected to deliver only about two hundred and fifty pounds thrust at forty thousand feet, possibly less, because of fixed losses and operating difficulties. Where air density is sufficient for satisfactory operation, and at reasonable speeds, each of these two types of thermal jet engines is much more economical in fuel expenditure than is the rocket variety."[9]

In the turbojet, the entering air is compressed by a rotary compressor, heated by the combustion of fuel at compressor pressure, released through a gas turbine that drives the compressor, and then ejected at high velocity through the rearward directed exhaust nozzle. Its main use is in airplanes.

LIQUID ROCKET PROPELLANTS

Several chemical systems for use as liquid fuels in the propulsion of rockets were studied in Germany during the recent war. "Selection of the chemicals was made very largely on the ground of availability rather than desirability. Each system had two main constituents, an oxidizing agent and a fuel. The constituents

reacted chemically in a combustion chamber at 30-40 atmospheres pressure. The products of combustion drove the rocket by passing out through a jet.

"The principal oxidizing agents considered were 98-100 per cent nitric acid with 5-10 per cent strong sulfuric acid added, liquid oxygen, which was difficult to handle, 80-85 per cent hydrogen peroxide with or without sodium or calcium permanganate, and ammonium nitrate. The principal fuels considered were methanol, ethanol, hydrazine hydrate, hydrazine plus methanol, 57 per cent xylidene plus 47 per cent tri-ethylamine, 8-hydroxyquinoline, furfuryl alcohol, vinyl ethyl ether, gasoline, diesel oil, Optol (a hydrogenated lignite tar fraction), and Ergal (a mixture of Optol, tetrahydrofuran, furfuryl alcohol, and aniline).

"A few mono-fuel systems were also studied. These included 65-85 per cent methyl nitrate in methanol, ammonium nitrate plus ammonia, ammonia and nitrous oxide, and tetra-nitromethane plus a solution of 8-hydroxyquinoline in 80-85 per cent hydrogen peroxide. None of these was ever developed to the point of large scale application, some being too dangerous and some unavailable under war-time conditions. The first mixture above was considered the most promising.

"Most of the rockets actually used were propelled either by a combination of liquid oxygen and methanol or ethanol, or by mixed acid (5-10 per cent sulfuric acid plus 95-90 per cent nitric acid) with an oxidizable substance. In the case of the V-2 rocket, the

starting cycle was in three steps. First, permanganate reacted with hydrogen peroxide giving superheated steam which drove a turbine connected to the pumps. The pumps deliver hydrogen peroxide and hydrazine hydrate in methanol solution to the combustion chamber, where an instantaneous, strongly exothermic reaction occurred. When the reaction chamber became hot enough, the permanganate and peroxide shut off automatically and the rocket drive was taken over by the liquid oxygen-alcohol combination. This system was also used, in principle, in experimental torpedoes and was engine tested for the trackless propulsion of submarines for high speed under water.

"In connection with the rocket program, the most important of the chemicals produced on a large scale for the first time was concentrated hydrogen peroxide. The usual 30-35 per cent commercial solutions made by the potassium persulphate, ammonium persulphate and persulphuric acid processes was brought up to 82-85 per cent strength by vacuum concentration in two stages. In the first, the solution was vaporized continuously from a retort maintained at 73 per cent concentration and the vapors, after passing through a separator, were fractionally condensed in a scrubbing tower as a 65 per cent product. This 65 per cent product was then fed into a second retort which was maintained at 80-85 per cent. The vapors were again fractionally condensed and the condensate returned to the retort, from which the finished product was overflowed. If especially pure solution was required, the product was drawn off

the bottom of the scrubber. Acidity was adjusted with phosphoric acid. The product was of very high purity and stability. One plant had a capacity of 500 metric tons per month; a second plant had a capacity of 1,200 tons per month; and a third plant was under construction with a projected capacity of 2,100 tons.

"The non-electrolytic processes were being investigated because of the shortage of platinum and stainless steel. One was based on the passage of hydrogen and oxygen through a silent electric discharge. The other was based on the reduction with hydrogen of 2-ethyl anthraquinone to 2-ethyl hodro-anthraquinone, followed by oxidation to 2-ethyl anthaquinone and hydrogen peroxide. Pilot plants had been operated on both processes and a large plant for the 2-ethyl anthraquinone process was under construction in spite of explosion hazards encountered in the pilot plant."[10]

In the United States, definite progress has been made in manned rocket-craft utilizing liquid propellants. A recent Army Air Force Fair at Wright Field had on exhibition the 6,000 pound thrust XCALT--6,000 and the 3,000 pound thrust X40ALD--3,000 units developed by the Aerojet Engineering Corporation for the Army Air Force. Burning a spontaneously combustible mixture of aniline and red fuming nitric acid, these power plants may well play a large part in future military aircraft design.[3]

The German Walter 109-509, propelling unit of the Me-163, also known as the HWK-509, uses hydrogen peroxide (85 per cent concentrate) and methyl alcohol as propellants. A 30 per cent

solution of hydrazine hydrate is contained in the methanol to initiate combustion upon coming in contact with the peroxide. Use of this chemical reaction to cause spontaneous combustion of the propellants eliminates need for an electrical ignition system. Power output is controllable by a throttle in the cockpit. Settings of the lever are "Off", "Idling", and three stages of power, varying from an estimated 650 pounds thrust in low, to 3,800 pounds thrust in the high power setting. One large fuselage tank and two small cockpit tanks contain 270 gallons of the syrupy hydrogen peroxide, and 130 gallons of hydrate-methanol solution are carried in the wing tanks. The fuel feed system is very similar to that used in the V-2. A portion of the peroxide is drawn off and decomposed to drive a turbine on a common shaft with two worm-type propellant pumps. The steam producer is a porcelain lined pressure vessel containing a wire screen on which are distributed pellets of calcium (or potassium) permanganate. Feeding a stream of peroxide over this catalytic agent results in violent decomposition into superheated steam and gaseous oxygen. These resultants are piped to the turbine nozzles and, after spinning the rotor, are exhausted through a rectangular waste nozzle below the fuselage.[3]

"The responsibility of developing an American counterpart of the German V-1 and a method of launching was assigned to the Army Air Force. With the invasion of the Normandy Coast, a complete German launching system was captured, dismantled, shipped, and re-erected at Eglin Field, Florida. The Germans used the

liquid chemical propellants 80-90 per cent hydrogen peroxide and calcium permanganate or sodium permanganate solutions. Little was known of the characteristics of hydrogen peroxide above 50 per cent concentration or of satisfactory methods of manufacture, handling, and storage. Chemical Warfare Service was requested to undertake this development and initiated the Fred Project with the specific problem limited to the launching of the Air Forces JB-2 flying bomb.

"A preliminary investigation led to the conclusion that three liquid chemical propellant systems should be investigated simultaneously, namely, hydrogen peroxide-permanganate, mononitromethane, and fuming nitric acid-aniline. As developed later, only the first system was found to be satisfactory for immediate use.

"The experiments indicate a wide range of conditions under which safe and successful operation can be achieved. The permanganate must enter the motor before or at least at the same time as the peroxide. Peroxide-permanganate concentrations from 5 to 32 per cent permanganate ion have been successfully used with wide variation in the ratio of peroxide to permanganate volume. The developed pressure is greater and its duration longer with the higher concentrations of peroxide."[1]

The lack of knowledge of how to handle, store, and ship hydrogen peroxide of more than 50 per cent concentration necessitated the studies of stability and corrosion of concentrated hydrogen peroxide and calcium permanganage. Commercial steel drums were

found satisfactory for shipment and storage of permanganates. For use with concentrated (80 to 90 per cent) peroxide, all surfaces required preconditioning by an acid wash followed usually by a peroxide soak. After such conditioning, Pyrex, aluminum 99.6 per cent plus, aluminum-magnesium alloys, tin-tantalum, cadmium, and stainless steel types 304 and 306 are suitable materials of construction for process equipment; Pyrex and aluminum 99.6 per cent plus are satisfactory for storage containers. Koroseal and polyethylene are suitable for gasket materials. Silicone grease is satisfactory as a lubricant and does not affect peroxide. The stability of peroxide is an inverse function of the amount of impurities present. Of the stabilizing agents investigated, phosphates give the best results; but above a certain concentration, additional amounts increase the rate of decomposition. Concentrated peroxide cannot be "detonated" by shock unless organic materials also are present.[1]

SOLID ROCKET PROPELLANTS

One of the first solid propellants used in rockets was black powder containing about 75 per cent potassium nitrate, 15 per cent charcoal, and 10 per cent sulfur. It was burned in the rocket motor chamber without air; temperature of combustion being about 3,300°F. However, during the period from 1865 to 1915, this black powder propellant became obsolete due to the discovery of smokeless powder with its higher energy content and the metallurgical advances which made high strength tubing of relatively low weight available

for use as containers for this newer, more powerful fuel.

Early in the experimental work preliminary to the development and production of solventless solid propellants for World War II rockets, it was recognized that a new type of rocket powder would be required. At that time, smokeless powder was being produced mostly by the solvent process in which the colloiding action takes place through the action of a mixture of organic solvents that are later removed and recovered after the powder has been granulated. While the solvent-type propellant was satisfactory in certain weapons like the "bazooka", it did not meet all of the following requirements for a satisfactory solid rocket propellant:

(1.) It must give a relatively long burning time--a rocket, unlike a shell, carries its source of energy and its combustion chamber while it is in flight. Maximum velocity is obtained by extending the time of application of gas pressure over as long a period as possible; this in turn keeps down the weight of metal in the chamber by reducing the pressures that the chamber must stand.

(2.) It must burn at a uniform rate--it is essential that the rate of gas production remain steady during the entire period of operation.

(3.) It should be smokeless.

(4.) It must function at relatively low pressure--the walls of the rocket motor must be as thin and light as possible, to permit the carrying of the maximum "pay load" of

explosives in the war head.

(5.) It must function satisfactorily over a wide range of temperatures.[6]

The limitations of the solvent process prevented the use of this method of manufacture for the production of propellant units much larger than those made for the "bazooka". It is difficult if not impossible to remove all of the solvent from large web grains, this violates the second listed requirement, because the presence of solvent reduces the burning rate of the powder and the layer containing the most solvent is at the greatest distance from a surface. While this method prohibited the use of propellant grains of large cross-sections, the smaller cross-sectioned powder had advantages in that facilities were readily available for manufacture of large quantities of this type of powder and such propellants with small webs were quicker burning. Small webs is an important feature in weapons like the "bazooka", in which burning is completed in the launcher tube, not only to prevent the operator from being burned by the flame, but also to give improved accuracy to the projectile. A quick-burning propellant, which causes a rocket to approach its maximum velocity before it leaves its launching guide, aids in improving the accuracy of a rocket fired from a stationary launcher, since fins of practical size do not exert appreciable restoring forces on the projectile except at relatively high velocities.[7]

In searching for a fuel that would meet all of the requirements

of a rocket propellant, a colloided, solventless nitrocellulose-nitroglycerine propellant was found to be the most satisfactory. This type of material would give a high specific impulse and could be manufactured with enough nitroglycerine to plasticise the nitrocellulose without requiring the use of volatile solvents or large amounts of inert plasticizers.

The process now used for the production of the solventless propellant is as follows: "The nitrocotton is manufactured to close tolerances as to nitrogen content, fineness, viscosity, solubility in ethyl alcohol and stability, and is delivered to the mixing operations with a high but constant moisture content. It is then delivered into a mixer tank with a cone agitator and slurried with ten times its weight of water. The required amount of nitroglycerin is introduced into the slurry through a lead distributor delivering it dropwise so it will be taken up immediately by the nitrocotton.

"The modifying chemicals are homogenized with water in a colloid mill to an emulsion of the consistency of thick cream and then introduced into the slurry mix and agitation continued for thorough mixing and uniform distribution. The slurry is then dewatered in a centrifugal wringer down to 30 per cent and the material is bagged and dried down to a moisture content of 6 to 10 per cent. Since the moisture varies throughout the drying container, blends of sizeable quantity are made to insure delivery of uniform moisture content material to the next operation. In this blending

operation, a small quantity of water-soluble ingredient is added. The blended paste is weighed in 6½ pound increments which are delivered to 14-inch by 30-inch differential rolling mills with heated rolls; as the water is cooked out, the material colloids. The sheet as delivered from the mill is about 0.030 inch thick, 14 inches wide, and 10 feet long. Two of these sheets are then combined on an even-speed rolling mill with a single sheet of reworked material to give a finished sheet weighing about 18 pounds. This is passed through a slitter where it is cut into strips from 4½ to 6 inches wide. These pass to a heated receiving and inspection table and from there to an ingenious carpet-rolling machine which prepares tight carpet rolls of the diameter of the press basket.

"Without permitting the material to lose temperature it is charged into mammoth extrusion presses, oil-draulic driven with heated baskets and water-jacketed dies, and extruded into the desired shape for final use under a pressure of about 8,000 pounds per square inch. The presses are located in bombproof rooms with 36 inch reinforced concrete walls and are operated by remote control. No operators are allowed in the press room during operation. A normal charge consists of 120 pounds of powder at a temperature of 110° F., with the die temperature held at 120° F. The extrusion cycle will last perhaps fifteen minutes.

"It is an interesting fact that the cross-section of the extruded strand will be larger than the die and the problem of correct die design has been critical since the dimensional tolerances on

the product are of the order of a few thousandths of an inch. At the completion of an extrusion, the ram is withdrawn from the press and the operators recharge the press and cut the extruded strand into lengths that are slightly oversize for the final grain dimension. Since internal fissure in the finished product is detrimental, each piece is then examined by x-ray or by a recently developed supersonic device and all fissured grains are returned for rework. Acceptable grains are annealed to relieve internal stress and to stabilize dimensions after which they are cut to exact weight or to exact length, submitted to various milling, machining and gauging operations and finally packed in a moisture-tight container for shipment. This latter requirement comes from a necessity to use this almost non-hygroscopic material at a moisture level well below its equilibrium point. For the same reason, almost all operations are conducted in air conditioned rooms."[5]

Early in the production of solventless powder it was found that under certain conditions some erratic results were obtained. A study of this problem led to the discovery of the very interesting phenomenon that partially burned propellant sticks showed fissures and "wormholes", both evidences of uneven burning. It was found that this erratic burning could be reduced by exposing the powder sheets to the sun. The powder contained the common stabilizing agent, diphenylamine, and the sunlight, by causing a partial decomposition of this compound, darkened the sheets. In order to determine whether the color was producing more uniform performance

7903

or whether this uniformity was due to some other cause, a dark pigment was added to the powder composition and the sunning was omitted. The results were even better than those given by irradiated sheets. A plausible explanation of this effect is that the temperature of the powder surface which is about to burn must be raised above its ignition point. This is accomplished primarily by conduction and radiation of heat from the flame. To be effective in heating the powder, the radiation must be absorbed, and this is favored by the presence of a dark pigment. In a perfectly transparent propellant, there would be no radiation effect. However, there are always small particles of uncolloided materials which will absorb sufficient heat to ignite the propellant well below the burning surface resulting in the development of small fissures which rapidly become larger as burning progresses. These fissures eventually communicate with the outside of the grain and increase its burning area, resulting in the erratic functioning of the rocket. On the other hand, the inclusion of a pigment in the propellant prevents the subsurface layers from absorbing radiant heat and uniform burning is attained.[5]

"It has long been known that salts of an alkali metal added to smokeless powder tend to give reduced flashes when fired from cannon. It was found that the use of such a salt in rocket propellants tend not only to decrease the intensity of the rocket flame, but also to improve certain burning characteristics. It is supposed that the beneficial effects of these salts result from the

increased radiant heat of the flame due to the presence of incandescent salt particles. In general, potassium salts are now included in most rocket propellants. They are used for such purposes because of their low hygroscopicity.

"With respect to the shape of these propellant grains, it is apparent that the perforated cylinders will maintain a nearly constant burning area; for as the outer surface area decreases during burning, the surface of the perforation through the center of the grain increases. This is desirable as it results in constant pressure functioning of the rocket and eliminates inefficient overdesigning of the motor tube based on a peak pressure rather than a constant maximum pressure. However, in order to use more economically the space within a given motor tube, grains of other cross-sections, designed to burn inward from their outer surface, have been developed. With any design of an inward burning grain, it can be geometrically shown that the burning area must decrease as unrestricted burning progresses. In order to avoid regressive burning, it is necessary to inhibit certain surface areas of this form of propellant. This is accomplished by covering these areas with an inert or very slow burning material.

"Along with the development of propellants for rockets, advances were made in the field of chemical analysis and tests. Quantitative and qualitative analysis of the ingredients of propellants by chromatographic separation has been developed to a high degree, and stability tests have been devised and improved.

Chromatographic analysis was originated by a Russian botanist, Tswett, in 1906. Because this method of analysis is somewhat unusual, a brief description will be of interest. The method is based on the separation of the constituents of a solution by its unidirectional flow through a column of adsorbent. The chromatographic column is formed by pouring a slurry of the adsorbent into a convenient-sized cylindrical glass tube, an average size tube being about one inch in diameter and ten inches long. The adsorbent is packed by strong suction into a solid column, resting on a plug of cotton in the bottom of the tube.

"After the column has been prepared, the mixture to be analyzed is dissolved in a small volume of some selected solvent from which the substances will be strongly adsorbed. The solution is poured upon the adsorbent and drawn by continuous suction into the column. Upon the subsequent addition of portions of the same or of a different solvent, the adsorbed substances migrate slowly at rates which depend upon their respective adsorption affinities. When the procedure is completed the various solutes are distributed throughout the adsorbent in a series of well-defined zones, separated from each other by portions of the column which are free of adsorbed material. The most strongly adsorbed substance will be nearest the top and the most weakly adsorbed nearest the bottom of the column. After removal of the column from the tube, the various zones are cut from the column and the individual zones are transferred to separate flasks and covered with an eluting

agent which removes the adsorbed material from the adsorbent. The resulting solution is separated from the adsorbent by filtration.

"Among other uses, chromatographic separation has been of great value in stability studies of propellants. Decomposition of a propellant may be measured by the determination of changes in its stabilizer. The stabilizer is usually present to the extent of about 1 per cent, and obviously its decomposition products would be hard to separate and analyze. But at least eighteen derivatives of diphenylamine have been separated by chromatographic means, and considerable information has obtained to show the mechanism of powder ageing."[7]

Smokeless powder is not easy to ignite; neither shock nor heat will easily initiate burning. However, the propellant of a rocket must be consistently and completely ignited within a very few milliseconds. Such ignition is particularly important when rockets are fired from planes, because an appreciable delay in getting the rockets away would cause the rocket to overshoot its target.[7]

To ignite the rocket propellant properly, black powder in a container within the rocket motor is inflamed by the spit from an electric squib. The black powder is hygroscopic; to keep it dry for proper functioning, it must be sealed in a moisture-proof container. The first Navy igniters employed a container made of brass crimped over a cellulose acetate cover. It was found difficult to form a permanent water tight seal between the brass and

the plastic. Later, igniters were molded entirely of cellulose acetate with threads molded directly into the cover and the case. This, with the use of cement, provided a snug, watertight, screw fit. It was found, however, that the cellulose acetate absorbed large quantities of nitroglycerine from the propellant and softened considerably. Tests were conducted on various plastic compositions to find a suitable material which had low nitroglycerine absorption. Certain ethyl cellulose formulations were found to have this desirable property, and this material has now replaced most of the cellulose acetate. Another material which has come into wide use for igniter cases in tin-plated sheet metal.[7]

Difficulties with some of the first igniters were traced to the wick-like action of the fabric insulation on the lead wires coming from the squib. Moisture traveled through the insulation into the match composition of the squib and desensitized it. This was corrected by the use of a plastic insulation.[7]

AIR STREAM JET FUELS

The three types of air stream jet engines are alike in fuel requirements. It is necessary only that the fuel possess high heating value and that it be capable of being fed continuously to the combustion zone. Practically, this means that the fuel must be liquid under the conditions of use. The feeding of solid fuel, even in finely divided powder form involves complicating mechanism; gaseous fuels occupy unduly large volumes per pound or per heat unit. Fuels that are gases at ordinary temperatures

and pressures can be used in liquified form provided the weight of the container necessary to hold them is not too great for practical purposes. These are the only ruling criteria in fueling jet planes. Many present commercial fuels meet them well. There are, of course, other specifications so desirable from a practical standpoint as to be virtual necessities. Both the raw fuel and the products of combustion must be free from solid abrasive particles that would erode the mechanism. The presence, for example, of silica or of combined silicon that would react in the flame to form silica is a serious drawback to any fuel. Other elements yielding similarly abrasive oxides must be excluded. Soot at extremely high velocities is also harmful. The fuel must remain liquid at the low temperatures encountered in flight at high altitudes. This requirement is met by many, but by no means all, of the commercial hydrocarbon fuels. Easy flow down to the required temperature of -40° F. is characteristic of gasolines and napthas, but some kerosenes become sluggish or actually congeal in this low temperature range.[4]

The flash point of the fuel should be high enough to eliminate danger in carrying the fuel in a plane. Gasoline has a flash point below normal atmospheric temperatures and thus its use involves a hazard of explosion which is particularly serious in military planes in combat. Consequently the specifications for fuel used in any military plane call for as high flash point as practicable. In jet fuel, this can be 105° F. If the flash point is made too high

the fuel is likely to freeze under operating conditions; conversely, too low a required freezing point leads to the inclusion in the fuel of hydrocarbons which unduly lower its flash point. Flash point is related to volatility and a low flash point is necessary for the proper vaporization of a fuel in a carburetor, which is not required by jet engines.[4]

The criterion of a clean fuel which burns without considerable residue is easily met, but the combination of low volatility, and consequently high flash point with an excessively low freezing point, is sometimes considerably more difficult to meet with practicable fuels. Either requirement alone would permit the use of immense volumes of petroleum products already available, but the combination of the two in a single fuel practically requires that it be especially refined for the purpose and thus makes it a special fuel.[4]

Also essential to the efficiency of a fuel in jet engines of present design is the ability of the fuel to burn in dilute mixtures with the large volumes of air used. Every combustible substance requires a definite proportion of air for its complete burning and it will burn in mixtures both more concentrated and more dilute than the ideal. However, outside a definite characteristic range of concentrations, it will not burn at all. The requirement of high dilution to keep temperatures down in jet engines limits usable fuels to those capable of burning at dilutions necessary to meet temperature restrictions. While this adds to the

complexity of the fuel problem, it still leaves a fairly wide selection available to the engineer in his efforts to produce satisfactory fuel for air stream jet engines.

Progress in the development of fuel for use in turbojet engines has been made public by Shell Oil Company, Inc., which has a laboratory devoted to these problems at Wood River, Illinois. Quotations from a recent press release are given below:

"The chief difficulty with the gas turbine is, of course, its very heavy fuel consumption. The efficiency of any heat engine depends on the range of temperature through which it can operate; and, unfortunately, the turbine cannot at present handle a temperature much in excess of 1200° F. In order to bring the temperature down to that level, we have to supply a very large amount of excess air, and since considerable energy is required to introduce into the combustion chamber, this makes for less over-all efficiency.

"The gas turbine generally burns a high-grade kerosene, and although its requirements may not be as restrictive as those of the present high-output piston engines, it will nevertheless present problems of combustion and handling. Any old fuel will almost certainly not do, because the wrong fuel will soot or coke the combustion chamber and impair the over-all efficiency. It will also reduce the life of the chamber, a very important point if the gas turbine is to take its rightful place in competitive commercial service.

"In view of the relatively high fuel consumption of the tur-

bine, the oil companies have cause to investigate the possibility of producing a fuel with a very high calorific value per unit volume, since we can deal more readily with weight than with bulk in the modern high-speed airplane. Unfortunately, problems in handling, such as low-temperature viscosity and freezing point, limit us in this direction. In view of all factors involved, it seems likely that a light kerosene will turn out to be the most satisfactory fuel for gas-turbined aircraft, delivering its power either through a propeller or a jet or a combination of both.

"It should not be imagined, however, that gas-turbine fuel will necessarily be cheap when delivered into the aircraft. It is true that the price of kerosene is considerably less than that of low-octane gasoline at the refinery. But the shipping and distribution costs of kerosene are likely to be much higher because of its smaller volume, so that the final price of the kerosene as it is pumped into the aircraft may be only slightly lower than that of gasoline.

"There is also a tendency to over-emphasize the relative safety of kerosene over gasoline. It is true that kerosene will be safer in many respects--particularly in the rate at which a fire spreads, once it is started. However, kerosene is easier to ignite, and a gas turbine has many more high-temperature surfaces from which ignition can start than a piston engine. Thus it is quite possible that there would be a greater incidence of minor fires in a jet aircraft, although probably a smaller incidence of serious ones."[8]

CONCLUSION

All of the information contained in this essay is of an unclassified nature, having been released to the public by the U.S. Armed Forces. It is very probable that a considerable quantity of more advanced and detailed information concerning fuels for jet propulsion has not yet been released by them. It will be interesting to observe these further details as they are released from time to time in the future.

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